METHOD OF MAKING AN OPTICAL FIBER PREFORM

Background and Summary

TECHNICAL FIELD

[0001] This invention relates to a method for producing an optical fiber preform and fiber. More specifically, the method relates to efficiently producing optical fiber preforms and fibers doped with an alkali metal oxide.

BACKGROUND OF THE INVENTION

[0002] Attenuation is a principal limiting attribute of optical fibers. Optical fiber loss, for example, plays an important role in setting the limiting distance between optical fiber amplifiers. This is particularly important in long distance and ultra-long distance networks such as, for example, undersea applications, where such amplifiers represent a significant system cost, as well as a major factor in system reliability. Consequently there is tremendous commercial interest in reducing attenuation to the lowest possible level.

[0003] Silica glass doped with an alkali metal oxide has been shown to be capable of reducing attenuation in optical fibers. Nevertheless, prior art methods of making optical fibers have been impractical for producing optical fiber preforms from which an alkali metal oxide doped optical fiber may be drawn as the alkali metal precursor compounds are impractical for direct deposition of alkali metal oxide doped soot to form preforms.

[0004] Manufacturing of optical fiber preforms, i.e., the article from which optical fiber is drawn, is typically accomplished by methods such as Outside Vapor Deposition (OVD), Vapor Axial Deposition (VAD), Modified Chemical Vapor Deposition (MCVD) and Plasma Chemical Vapor Deposition (PCVD). In accordance with one method, an optical fiber preform is formed by an OVD method. In the OVD method, silica-containing soot **20** is deposited onto a rotating and traversing mandrel **22** as indicated by arrows A and A' of FIG. 2 to form a porous core soot preform **24**. To form the soot **20**, a glass precursor **26** is provided, preferably in gaseous form, to the flame **28** of a burner **30**.

The flame **28** is formed by combusting a fuel **32**, such as methane, while providing a combustion supporting gas, such as oxygen **34**. The core soot preform **24** may be up-doped with a dopant such as germania oxide, for example, to raise its refractive index. This may be accomplished, for example, by providing a glass precursor **26**, such as $SiCl_4$, to the burner **30** in gaseous form along with a gaseous dopant compound, such as $GeCl_4$. The doped silica-containing soot preform **24** is then dried and consolidated in a consolidation furnace **32**, such as shown in Prior Art FIGS. 3 and 4 to form a consolidated core blank **34**. A helium and chlorine gas atmosphere, for example, in the consolidation furnace is used to dry the preform and remove water prior to vitrification into glass at a temperature of about 950°C to 1250°C. Pure helium is generally provided during consolidation and the temperature is higher, for example, between about 1390°C to 1535°C.

[0005] Following consolidation, next, as shown in FIG. 5, the consolidated core blank **34** is placed in a cane draw furnace **36** and is stretched into a length of core cane **38** from which multiple core cane segments **40** are derived. At the same time, the centerline aperture is closed by application of, for example, a vacuum. The draw tension and preform downfeed rates (indicated by arrow B) are controlled by suitable control method **42** to provide a core cane length **38** of preferably substantially constant, predetermined diameter d_o. The diameter d_o is controlled by feedback of a measured diameter signal from an appropriate non-contact sensor **44** to the control apparatus **42**. In response, the controls **42** may adjust the tension applied at the tension apparatus **46** whereby lowering the tension raises the diameter d_o and raising the tension lowers the diameter d_o. At predetermined lengths, the cane is cut, such as by a flame cutter **48**, to form a predetermined length core cane segment **40** (FIG. **6**). This core cane **40** represents the first segment **10** of the final preform, as illustrated in FIG. **1**.

[0006] In the final step, the core cane segment is overclad with silica-containing soot. This step looks identical to FIG. 2 except that the mandrel is now the previously made core cane **40**. The soot deposited is preferably silica soot formed by providing the glass precursor **26** such as $SiCl_4$ to the flame **28** and oxidizing the precursor to form SiO_2. Next, the soot-laden core cane **50** is placed in a furnace **52** as is described in Berkey U.S. Pat. No. 4,629,485 and is consolidated, as shown in FIG. **7**. Preferably the overcladding

comprises essentially SiO_2. The soot preform is dried and consolidated as heretofore mentioned to form the final consolidated optical fiber preform **54**. The resulting final consolidated preform **54** is then placed in a draw furnace **56** as shown in FIG. 8, heated and drawn into an optical fiber **58** in a helium gas atmosphere by conventional methods and apparatus. The fiber **58** is then cooled in cooling chamber **60** and measured for final diameter by non-contact sensor **62**. One or more coatings are applied and cured by coating apparatus **64**, as is also conventional. During draw, the fiber **58** passes through a tension assembly **66** whereby tension is applied to draw the fiber **58** from the preform **54**. The tension is controlled via control apparatus **68** to maintain the fiber diameter at a predetermined set point. Finally, the coated fiber **70** is wound by feedhead **72** onto a fiber winding spool **74**.

SUMMARY OF THE INVENTION

[0007] One broad aspect of the invention includes a method of making an optical fiber preform comprising the steps of inserting a first glass rod into a first glass tube, heating the first glass rod and the first glass tube; and flowing a carrier gas comprising oxygen and an alkali metal vapor between the first glass rod and the first glass tube wherein the alkali metal vapor comprises an alkali metal selected from the group consisting of K, Na, Li, Cs, Rb, and combinations thereof. Preferably, the water content of the first glass rod is less than about 100 ppb; more preferably less than about 20 ppb. The first glass rod preferably comprises less than about 0.05 wt. % chlorine; more preferably less than about 0.02 wt. %; and most preferably less than about 0.01 wt. %.

[0008] The manufacturing method in accordance with a first embodiment of the invention comprises the steps of forming a first glass rod, or core cane segment, which preferably has a germania dopant therein, providing a delta of between about 0.2%-3%, inserting the segment into a first glass tube (sleeve), preferably formed by an inside method such as MCVD or PCVD, doping the rod-tube assembly with an alkali metal oxide, and then collapsing the sleeve onto the rod to form a second glass rod. The second glass rod preferably comprises an alkali metal oxide in a peak concentration of at least about 0.01 wt. %; more preferably at least about 0.1 wt. %; and most preferably between about 0.1 wt. % and 5 wt. %. The second glass rod may then be drawn to form a third

glass rod. Additional glass may be formed on the third glass rod to form an optical fiber preform. The optical fiber preform may be drawn into an optical fiber by conventional drawing methods.

[0009] The first glass rod, in accordance with the invention, is preferably formed by an OVD method wherein a core soot region is formed by depositing silica-containing soot onto an outside of a rotating deposition surface, the core soot region is then dried and consolidated in a consolidation furnace to form a consolidated core blank, followed by drawing from the consolidated core blank the core cane segment having an outer dimension d_o.

[0010] In accordance with another embodiment of the invention, the first glass rod may be removed from the first glass tube at the completion of the alkali metal oxide doping step, after which additional glass may be formed on the first glass rod. The first glass rod preferably comprises an alkali metal oxide in a peak concentration of at least about 0.01 wt. %; more preferably at least about 0.1 wt. %; and most preferably between about 0.1 wt. % and 5 wt. %. Preferably, the additional glass is formed by depositing soot. The glass soot may then be dried and consolidated to form an optical fiber preform. The optical fiber preform may be drawn into an optical fiber doped with an alkali metal oxide. Alternatively, the additional glass may be formed by inserting the first glass rod into a second glass tube, and collapsing the glass tube onto the first glass rod to form and optical fiber preform. The optical fiber preform may then be drawn into an optical fiber doped with an alkali metal oxide.

[0011] In accordance with another embodiment of the invention, a method of manufacturing a multi-segment optical fiber doped with an alkali metal oxide is provided comprising the steps of forming a first glass rod by depositing silica-containing soot onto an outside of a rotating deposition surface to form a soot preform, consolidating the soot preform in a consolidation furnace thereby forming a consolidated blank, drawing from the consolidated blank to form at least one glass rod (core cane segment) having an outer dimension d_o; forming additional layers of glass on an inside of a first glass tube (sleeve) wherein the sleeve tube includes one or more down-doped radial portions and one or more up-doped radial portions, preferably as compared to silica, inserting the first glass rod into the first glass tube, flowing an alkali metal vapor between the core cane and the

sleeve tube, and collapsing the sleeve tube around the first glass rod to form a second glass rod. The second glass rod preferably comprises an alkali metal oxide in a peak concentration of at least about 0.01 wt. %; more preferably at least about 0.1 wt. %; and most preferably between about 0.1 wt. % and 5 wt. %. The second glass rod may then be drawn to form a third glass rod comprising multiple core segments, forming cladding glass on an outside of the third glass rod to form an optical fiber preform, and drawing the optical fiber from the optical fiber preform. It should be recognized that the one or more down-doped portions may include a moat and a gutter, for example. Further, the one or more up-doped portions may include multiple spaced rings.

[0012] Other features and details of the present invention will be apparent from the appended specification, claims and drawings.

BRIEF DESCRIPTION OF THE FIGURES

[0013] FIG. 1 illustrates a schematic depiction of a single segment profile in accordance with the prior art.

[0014] FIG. 2 illustrates a prior art OVD method for forming a soot preform.

[0015] FIGS. 3 and 4 illustrates partially cross-sectioned side views of a soot preform and a consolidated core blank in accordance with the prior art.

[0016] FIG. 5 illustrates a partially cross-sectioned side view of a core cane draw furnace in accordance with the prior art.

[0017] FIG. 6 illustrates a cross-sectioned side view of a core cane segment in accordance with the prior art.

[0018] FIG. 7 illustrates a partially cross-sectioned side view of a preform in a consolidation furnace in accordance with the prior art.

[0019] FIG. 8 illustrates a partial cross-sectioned side view of an optical fiber draw apparatus in accordance with the prior art.

[0020] FIG. 9 illustrates a perspective view of a process of assembly of the core cane into the sleeve in accordance with the present invention.

[0021] FIG. 10 illustrates a cross sectional side view of exposing a core cane segment and a sleeve assembly to an alkali metal vapor in accordance with an embodiment of the present invention.

[0022] FIG. 11 illustrates a cross section view of an apparatus for supplying an alkali metal vapor in accordance with the present invention.

[0023] FIG. 12 illustrates a schematic partially cross-sectioned view of the step of collapsing a cladding tube onto the multi-segmented core cane preform in accordance with an embodiment of the present invention.

[0024] FIG. 13 illustrates a partially cross-sectioned side view of a core cane draw assembly for producing a core cane in accordance with the present invention.

[0025] FIG. 14 illustrates a partially cross-sectioned view of an assembly for silica cladding the core cane in accordance with an embodiment of the present invention.

[0026] FIG. 15 illustrates a perspective view of the assembly of a length of the core cane into a silica cladding tube in accordance with an embodiment of the present invention.

[0027] FIG. 16 illustrates a cross sectional view of the soot preform being consolidated in accordance with an embodiment of the present invention.

[0028] FIG. 17 illustrates a cross-sectional side view of the consolidated preform in accordance with an embodiment of the present invention.

[0029] FIG. 18 illustrates a schematic partially cross-sectioned view of the step of collapsing a cladding tube onto the multi-segmented core cane preform in accordance with an embodiment of the present invention.

[0030] FIG. 19 illustrates a perspective view of an embodiment of the consolidated preform in accordance with an embodiment of the present invention.

[0031] FIG. 20 illustrates a schematic depiction of a relative refractive index profile of a consolidated preform of FIG. 19.

[0032] FIG. 21 illustrates an MCVD method of forming additional glass layers in a glass tube to form a sleeve tube.

[0033] FIG 22 illustrates a sleeve tube having multiple layers of up-doped and/or down-doped glass deposited on an inside surface of the tube.

[0034] FIG. 23 illustrates a PCVD method of forming additional glass layers in a glass tube to form a sleeve tube.

[0035] FIG. 24 illustrates a relative refractive index profile of an optical fiber having multiple core segments.

DETAILED DESCRIPTION OF THE INVENTION

[0036] Reference will now be made in detail to the present preferred embodiments of the invention with reference to the attached drawings. Wherever possible, the same or similar reference numerals shall be used throughout to refer to the same or like parts.

[0037] According to a first embodiment of the present invention, a method of manufacturing an optical fiber preform doped with an alkali metal oxide is provided. As best illustrated in FIGS. 2-5, the method for forming the optical fiber preform comprises a first step of forming at least one core cane segment **40** having an outer dimension d_o. The core cane is preferably formed in accordance with the prior art OVD method described herein. In particular, a core soot region **23** is formed by depositing doped silica-containing soot **20** onto an outside of a relatively rotating and translating deposition surface **25**. At first, the surface is a tapered mandrel and thereafter is the surface of the soot already deposited. The soot **20** is formed by providing a glass precursor **26** in gaseous form to the flame **28** of a burner **30** to oxidize it. Fuel **32**, such as methane (CH_4), and combustion supporting gas **34**, such as oxygen, are provided to the burner **30** and ignited to form the flame **28**. Mass flow controllers, labeled V, meter the appropriate amounts of suitable dopant compound **33**, glass precursor **26**, fuel **32** and combustion supporting gas **34**, all preferably in gaseous form, to the burner **30**. The glass former compounds **26**, **33** are oxidized in the flame **28** to form the generally cylindrically-shaped soot region **23**. In particular, it is desirable that the dopant compound **33** includes an index raising dopant, such as a germanium compound.

[0038] Next, the soot preform **24** including the soot region **23** is consolidated in a consolidation furnace **32** thereby forming a consolidated core blank **34** as is shown in FIGS. 3 and 4. The soot preform **24** is suspended inside a pure quartz muffle tube **27** of the furnace **32** by a holding mechanism **21** and exposed to a drying atmosphere of about 98% to 99% helium and 1% to 2% % chlorine gas at a temperature of between about 950°C and 1250°C for between about 0.5 and 4.0 hours. The furnace temperature is then raised and the preform **24** is consolidated preferably in an atmosphere of pure helium at a temperature of between about 1390°C and 1535°C to form the consolidated core blank

34. Preferably, gradient sintering is employed whereby the soot preform **24** is driven down through a hot zone of the furnace **32** at a rate of about 2-20 mm/minute.

[0039] As illustrated in FIGS. 5 and 6, the consolidated core blank **34** is next placed in a core cane draw furnace **36** and at least one rod-shaped core cane segment **40** (FIG. 6) having an outer dimension d_o is drawn therefrom. The preform blank **34** is heated to a temperature between about 1700°C and 2000°C until a gob drops. Once a suitable amount of trash glass is stripped, the controls **42** then control the tension applied to the cane by suitable control signals to a tension mechanism **46**, shown here as two tractor wheels, to draw down the cane **38** at the proper speed. In this way, it is possible to derive a length of core cane **38** having an outer diameter dimension of between about 1 mm and 10 mm.

[0040] The diameter of core cane **38** is monitored by a non-contact sensor **44** and provides to the control system **42** a signal thereof. The controls **42** compare the sensed diameter signal from sensor **44** to a predetermined set diameter stored in memory and thereafter commands an appropriate adjustment, if any, to the tension to maintain the set diameter d_o . Controls **42** also control the down feed rate of the blank **34**. Preferably, that rate is held constant. Arrow B indicates the down feed of the blank **34**. As a predetermined length of the core cane **38** passes through the tension assembly **46**, as determined by the controls, a cutter **48**, such as a flame cutter, is activated. The cutter severs the cane **38** into predefined lengths of core cane segments **40** (FIG. **6**). It should be recognized that the core cane **40** produced corresponds to the innermost core of the preform and fiber and preferably includes the germania dopant. In a preferred embodiment, the core cane segment **40** has a Δ_1 of between 0.2% and 3% as compared to the silica cladding, where $\Delta_c = 0$ and $\Delta_1 = (n_1 - n_c)/n_c$, where n_1 is the peak refractive index of the first segment **10**, and n_c is the refractive index of the cladding **12**. First segment **10** may have a parabolic profile (**11a**), or a step-like profile (**11b**). Preferably, core cane segment **40** comprises less than about 100 ppb by wt. of water; more preferably less than about 20 ppb by wt. By water we mean the hydroxyl radical OH. OH is responsible for an absorption peak at or about 1383 nm and which absorption peak may extend into one or more operating wavelength regions of an optical fiber. This absorption peak may have a detrimental effect on the optical loss, or attenuation, of an optical fiber

which may eventually be formed from core cane segment **40**. Preferably, core cane segment **40** comprises less than about 0.05 wt. % Cl; more preferably less than about 0.02 wt. %; most preferably less than about 0.01 wt. %.

[0041] In accordance with the next step in the method invention, the core cane segment **40** of FIG. 10 having a dimension d_o of between about 1 mm and 10 mm, preferably between about 5 mm and 10 mm, and more preferable between about 8 mm and 10mm, is inserted into glass sleeve tube **76**, as is illustrated in FIG. 9. The sleeve **76** has an inner dimension d_i of between about 17 mm and 26 mm. Core cane segment **40** is positioned concentrically within sleeve **76**. In some cases it may be desirable to decrease the diameter of sleeve tube **76**, and therefore d_i, prior to inserting core cane segment **40** into sleeve **76**. Preferably, the distance between an inside surface of sleeve **76** and an outside surface of core cane segment **40** is less than about 8 mm, more preferably less than about 5 mm, and most preferably less than about 3 mm. This may be accomplished, for example, by heating sleeve tube **76** on a conventional glass working lathe or by heating sleeve tube **76** into a suitable furnace. Glass sleeve **76** may be substantially pure silica, or glass sleeve **76** may comprise one or more dopants. For example, glass sleeve **76** may comprise F or Ge. Preferably, glass sleeve **76** comprises less than about 0.05 wt. % Cl; more preferably less than about 0.02 wt. %; most preferably less than about 0.01 wt. %. Preferably, glass sleeve **76** comprises less than about 100 ppb by wt. of water; more preferably less than about 20 ppb by wt.

[0042] In the next step of the present method, as best shown in FIG. 10, the nested sleeve **76** and core cane **40,** which form assembly **78,** are inserted in the draw furnace **56** and assembly **78** is heated while a mixture of carrier gas and alkali metal vapor **82** is flowed through a space **80**, as indicated by arrows **82**, formed between the core cane segment **40** and the sleeve **76**. The alkali metal vapor is transported through space **80** by a carrier gas comprising oxygen. The carrier gas may also comprise an inert gas, such as argon or helium. The carrier gas preferably comprises at least about 15% oxygen; more preferably at least about 20% oxygen. However, oxygen concentrations of up to 100% may be used. The carrier gas is preferably flowed at greater than about 0.5 standard liters per minute (SLPM); more preferably between about 0.5 and 1.0 SLPM.

[0043] The alkali metal vapor may be formed by heating a suitable alkali metal source compound. The alkali metal source compound preferably comprises an alkali metal selected from the group consisting of K, Na, Li, Cs, Rb, and combinations thereof. Preferably, the alkali metal source compound is an iodide or bromide of the alkali metal. For example, the alkali metal source compound may be KBr, or KI. In the embodiment shown in FIG. 12, a chamber **84** for heating the alkali metal source compound is connected at one end of assembly **78**. Chamber **84** contains a predetermined amount of alkali metal source compound **86** and is heated by heat source **88**. For example, at least about 25g of alkali metal source compound may be used in chamber **84**; more preferably at least about 35g, most preferably at least about 50g. Heat source **88** may be, for example, a combustion burner or a resistance heater. The oxygen containing carrier gas **85** is flowed into chamber **84** where the carrier gas mixes with and transports the alkali metal vapor through space **80**. As the oxygen contained within the carrier gas contacts the heated alkali metal vapor, an alkali metal oxide is formed. The alkali metal oxide contacts and diffuses into the inside surface of sleeve **76** and the outside surface of cane **40**, thereby forming an alkali metal oxide doped glass.

[0044] Preferably, relative motion is provided between assembly **78** and furnace **56** as indicated by arrow C in FIG. 11. For example, relative motion may be obtained by passing assembly **78** through furnace **56**. Alternatively, assembly **78** may be stationary while furnace **56** moves parallel to the longitudinal axis of assembly **78**. Both assembly **78** and furnace **56** may move to provide relative motion. In a preferred embodiment, assembly **78** is passed through furnace **56** for at least one pass while the mixture of carrier gas and alkali metal vapor flows through space **80**; more preferably at least about 2 passes, more preferably still, at least three passes; and most preferably at least four passes. Preferably, the temperature of furnace **56** is at least about 2000C, more preferably at least about 2040°C; and most preferably at least about 2100°C. Preferably, the relative motion between assembly **78** and furnace **56** is at least about 1 cm/s, more preferably at least about 2 cm/s; and most preferably at least about 3 cm/s.

[0045] In the next step of the present method, as best shown in FIG. 12, assembly **78** is inserted in the draw furnace **56** and sleeve **76** is heated and collapsed around core cane segment **40**. This forms optical fiber precursor **90**. The temperature in furnace **56** is

preferably set between about 1700° C and 2100° C. The collapse step may be accomplished, for example, by moving assembly **78** through furnace **56**. Alternatively, the step of collapsing to form optical fiber precursor **90** may be performed in a lathe (not shown) by passing a suitable heat source along the nested segment and sleeve while simultaneously rotating them. Preferably, precursor **90** comprises an alkali metal oxide dopant in a peak concentration of at least about 0.01 wt. %; more preferably at least about 0.1 wt. %; and most preferably between about 0.1 wt. % and 5 wt. %.

[0046] Next, as best shown in FIG. 13, after the step of collapsing, optical fiber precursor **90** is stretched in, for example, draw furnace **56** to form a length of cane **92**. The length of cane **92** is drawn to a diameter dimension of d_o' as shown in FIG. **13**. Multiple core canes **94** are cut from the length **92**. These segments **94** then have silica-containing cladding applied thereto to form on an outside cladding thereof.

[0047] In a preferred embodiment, silica-containing cladding soot **122** is applied to the outside of cane segment **94** in a conventional OVD process, as shown in FIG. **14**. In the OVD process, glass precursor **143**, such as $SiCl_4$ or octamethylcyclotetrasiloxane, is provided in gaseous form to burner **126**. Burner flame **130** oxidizes precursor **143** and forms silica-containing soot **122**. Soot **122** is deposited onto the outside of rotating length **94** by the traversing burner (as indicated by arrow E) to the appropriate predetermined thickness to form overclad soot preform **120**.

[0048] As best shown in FIG. 17, soot-laden preform **120** is inserted in a consolidation furnace **129** and gradient sintered in a hot zone having a temperature of between about 950° C. and 1535° C. at a down drive speed of about 2-20 mm/minute, and most preferably about 5 mm/minute. The result is consolidated preform **150**, as best shown in FIG. 18.

[0049] In an alternate method, as best shown in FIGS. 15 and 18-19, the length of core cane **94** is inserted into a silica-containing glass cladding tube **96** (FIG. 16). Then, cladding tube **96** is collapsed onto cane segment **94** to form preform **150**. Preferably, this is accomplished in a suitable lathe apparatus (not shown for clarity). The cladding tube **96** and cane segment **94** are simultaneously rotated in the lathe and subjected to sufficient heat from a flame or other heat source traversing along the length as indicated by arrow F. A chlorine gas **98** may be provided to the gap between the cane **94** and tube **96** prior to

the step of collapsing. The result is an optical fiber preform **150** including the core cane **94** and silica-containing cladding tube **96** which is now ready for being transferred to a draw furnace to draw optical fiber therefrom. Optical fiber is drawn from the preform **150** in a conventional manner as was earlier described with respect to FIG. **8**.

[0050] Thus, it should be recognized that the method in accordance with this embodiment of the invention provides for manufacturing an optical fiber preform doped with an alkali metal oxide by forming a core cane, forming the sleeve tube, inserting the core cane into the sleeve, flowing a mixture of oxygen and an alkali metal vapor between the core cane and the sleeve, and collapsing the sleeve around the core cane to form an optical fiber precursor. Next, the optical fiber precursor is stretched into a second core cane. A cladding portion is then formed around the second core cane to form an overclad assembly, and the overclad assembly is consolidated to form the alkali metal oxide doped optical fiber preform. The preform is then drawn into optical fiber in accordance with conventional methods as shown in FIG. 8, for example.

[0051] In addition to these embodiments, persons skilled in the art can see that numerous modifications and changes may be made to the above invention without departing from the intended scope thereof. For example, in another embodiment, core cane **40** may be removed from sleeve **76** before the collapse step of sleeve **76**. Additional glass may then be formed on core cane **40** in the method shown, for example, in FIG 2. Preferably, the additional glass is formed by depositing soot onto the glass core cane **40**. Preferably, the glass soot is substantially pure silica. The resulting core cane-soot body is consolidated to form an optical fiber preform which may be drawn into an optical fiber in accordance with the method depicted in FIG. 8.

[0052] In yet another embodiment, as best illustrated in FIGS. 21-24, one or more additional glass layers may be formed on an inside of a glass tube **63** to form sleeve tube **76** prior to inserting core cane **40** into glass sleeve **76**. The glass sleeve tube **76** preferably includes a down-doped inner radial portion **67**, as compared to silica, formed at an inner portion of sleeve **76**, and a outer radial up-doped portion **61**, as compared to silica, formed at an outer portion of the sleeve **76**. In the FIG. 21 embodiment, the glass sleeve tube **76** is formed by introducing gaseous glass precursor, such as $SiCl_4$ and, preferably, a dopant compound into the end and inside cavity **59** of the glass tube **63**. The glass

precursor **43** and dopant compound **47** are provided in gaseous form to dope the glass to achieve the desired refractive index profile for the sleeve **76** as a function of radial dimension thereof.

[0053] In particular, the up-doped segment **61** is preferably formed by providing an index-raising dopant compound **47**, such as a germanium-containing dopant compound, in gaseous form into the cavity of glass tube **63** along with the glass precursor **43**. One preferred compound is $GeCl_4$. Others include Cl_2, $POCl_5$, $TiCl_4$, $AlCl_3$ or any other suitable index-raising dopant.

[0054] The down-doped segment **67** is next formed by introducing an index-lowering dopant compound **47**, such as F_2, CF_4, C_2F_4, SF_6, SiF_4, C_2F_6 or any other suitable fluorine-containing compound in gaseous form into the inner cavity of the tube **63**. As the glass precursor **43** (e.g. $SiCl_4$) and dopant compound **47** are introduced into glass tube **63**, the tube is rotated by a motor **49** at rotational speed of between about 20 and 60 rpm. Soot is formed in the tube and, by the aid of an axially traversing flame **73***a* of a burner **73***b* that moves along the length of the tube **63** (as indicated by arrow D), the soot is heated and substantially simultaneously converted into consolidated glass on the inside of tube **63**. The burner **73***b* operates on any suitable fuel **32**, such as CH_4, and suitable combustion supporting gas **34**, such as O_2. Other gases may be included such as C_2H_2, H_2, and/or N_2. Preferably, sleeve tube **76** has the refractive index profile as indicated in FIG. 24 thereby providing at least one up-doped segment **146** and at least one down-doped segment **145**, as shown. FIG. 24 also shows a central core segment **144**, formed from core cane 40, and cladding **148**, which may be added at the completion of the draw step during which the optical fiber precursor is formed, as previously described. Preferably, the down-doped segment of the sleeve **76** is achieved by including a fluorine dopant. In particular, it is desired that down-doped moat segment include a Δ_2 between about -0.1% and -1.2%. Sleeve tube **76** is shown in FIG. **22**. Once the layers **67** and **61** are formed inside of tube **63**, glass tube **63** remains as part of sleeve **76**. Core cane segment **40** may then be inserted into sleeve **76** as previously described.

[0055] Alternatively, the sleeve **76** may be produced by a Plasma Chemical Vapor Deposition (PCVD) method, as shown in FIG. **23**. In the PCVD method, a glass precursor **43** and dopant compound **47** are provided into cavity **59** of the silica glass tube **63** in

gaseous form as in the before-mentioned MCVD process of FIG. **21** . However, in this case, the cavity of the silica tube **63** is held at a low pressure (typically 10-20 Torr) and energy is provided by a microwave resonator **69** (typically powered by 2-6 kW). The microwave resonator **69** surrounds the tube **63**, and directs microwaves through the wall of the tube **63** to produce plasma **71** within the tube **63**. The microwaves heat the inside of the tube **63** and the gases to about 1200°C-1400°C, thus promoting chemical reactions, and causing the formation of consolidated glass inside of the tube **63**. PCVD apparatus are taught in U.S. Pat. No. 4,877,938 and U.S. Pat. No. 4,714,589, for example. The dopants introduced are provided in such amounts as to provide at least one up-doped and at least one down-doped segment, as shown in FIG. 24. Similar to the MCVD process, any suitable motor **49** rotates the tube **63** and any suitable traverse assembly (not shown) moves the generator **69** back and forth (as indicated by arrow D) along the length of the tube **63**.

Example

[0056] A silica glass core cane doped with GeO_2 was placed in a General Electric GE-098 glass tube to form an assembly. The core cane had an outside diameter of 9.8 mm. The glass tube had an outside diameter of 25 mm and an inside diameter of 21 mm. An alkali metal compound chamber was formed at a first end of the glass tube comprising the assembly. The chamber was loaded with approximately 50g of KBr. The assembly was movably and vertically supported in a conventional draw furnace. A separate furnace was used to surround and heat the KBr chamber. The KBr chamber furnace was used to heat the KBr to a temperature of about 600°C. The draw furnace was heated to a temperature of about 2100°C. The assembly downstream of the chamber was passed through the draw furnace at a downfeed rate of approximately 7 cm/min to fire polish the assembly, thereby removing contaminants which might be adhered to the glass surfaces, and smoothing the glass surfaces. Unless otherwise noted, each return pass (return to the initial starting position) throughout the process was accomplished by withdrawing the assembly through the furnace at a rate of about 25 cm/min.

[0057] Once the fire polish step was completed, the KBr was heated to a temperature of about 1000°C. The draw furnace was heated to a temperature of about 2040°C. The

assembly downstream of the KBr chamber was passed through the draw furnace at a downfeed rate of about 2.5 cm/min. The carrier gas flow through the KBR chamber and the interstitial region of the assembly between the core cane and the glass tube was about 1 SLPM. The carrier gas was 100% oxygen. A second pass was made with a draw furnace temperature of about 2060°C. The downfeed rate of the second pass was approximately 2.5 cm/min. The carrier gas flow rate was 1 SLPM. A third pass was made with the draw furnace at a temperature of about 2080°C. The carrier gas flow rate was 1 SLPM and the downfeed rate was about 2.5 cm/min. At the completion of the third pass, the KBR chamber furnace temperature was reduced to 600°C. The draw furnace temperature was increased to 2100°C and the assembly downstream of the KBr chamber was passed through the draw furnace at a downfeed rate of 2.5 cm/min to collapse the assembly and close the space between the core cane and the glass tube. The carrier gas flow rate was maintained at 1 SLPM. The downfeed rate during the first collapse pass was 2.5 cm/min. A second collapse pass was made with the draw furnace temperature maintained at 2100°C. The downfeed rate of the assembly was about 2 cm/min, and the carrier gas flow rate was 1 SLPM. A third collapse pass was made with the draw furnace temperature maintained at 2100°C. The downfeed rate was reduced to 2 cm/min, and the carrier gas flow rate was maintained at 1 SLPM. A seal pass was made with the draw furnace temperature at 2100°C to ensure adequate sealing of the the assembly. The downfeed rate of the assembly was reduced to about 1.5 cm/min. The carrier gas flow rate was 1 SLPM. The resulting K_2O doped rod was measured across a diameter of the rod for the concentration of K_2O and GeO_2 using an electron microprobe. A plot of the concentration of K_2O (**98**) and GeO_2 (**100**) contained in the rod as a function of position across the rod diameter is shown in FIG. 20. FIG. 20 shows a core region doped with GeO_2 in a peak amount of about 5 wt. %. The rod also contains K_2O as a ring surrounding the core region. The K_2O is in a peak amount of about 0.33 wt. %.